The Dark Matter – Collider Connection

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1 DM and Missing E_T

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Counter–examples: axions; dark atoms; primordial black holes; keV neutrinos: not covered in this talk. Note: Proves that LHC does not "recreate conditions of the early universe"!

Thermal production of DM particles χ

- *Assume* χ was in full thermal equilibrium with SM particles at sufficiently temperature T:

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- $$\Longrightarrow \Omega_\chi h^2 \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma(\chi\chi \to \mathrm{SM}) v \rangle}$$
- Indicates weak-scale $\chi\chi$ annihilation cross section! ("WIMP miracle")

WIMPs and Early Universe

$\Omega_\chi h^2$ can be changed a lot in non–standard cosmologies (involving $T \gg T_{\rm BBN}$):

- Increased: Higher expansion rate $H(T \sim T_F)$; additional non–thermal χ production at $T < T_F$

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Determining $\sigma(\chi\chi \to {\rm SM})$ allows probe of very early Universe, once χ has been established to be "the" DM particle! e.g. MD, Iminniyaz, Kakizaki, arXiv:0704.1590

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Either way, χ interactions with SM particles are too weak to give missing E_T signal, unless χ has "partners" that can be produced via gauge interactions (ex.: gravitino $\tilde{G}$, axino $\tilde{a}$)

Cannot predict missing E_T from $\chi\chi$ production

- Only know *total* $\chi\chi \to \mathrm{SM}$ cross section; contribution of specific final states (e^+e^-, $u\bar{u} + d\bar{d}$) *not* known

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- $\Omega_\chi h^2$ determined from $\sigma(\chi\chi \to \mathrm{SM})$ near threshold ($T_F \simeq m_\chi/20 \Longrightarrow s \simeq 4m_\chi^2$). At colliders need ≥ 3 body final state to get signature (e.g. $e^+e^- \to \chi\chi\gamma,\ q\bar{q} \to \chi\chi g$) $\Longrightarrow$ typically need $\sigma(\chi\chi \to \mathrm{SM})$ at $s \sim 6 \text{ to } 10m_\chi^2$!

“Model-independent” approach

Goodman et al., arXiv:1005.1286 and 1008.1783; Bai, Fox, Harnik, arXiv:1005.3797; Wang, Li, Shao, Zhang, arXiv:1107.2048; Fox, Harnek, Kopp, Tsai, arXiv:1103.0240

Parameterize χ interaction with relevant SM fermion through dim–6 operator; e.g. for hadron colliders:

$$\mathcal{L}_{\rm eff} = G_\chi \bar{\chi} \Gamma_\chi \chi \bar{q} \Gamma_q q$$

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χ Majorana $\Longrightarrow \Gamma_\chi \in \{1, \gamma_5, \gamma_\mu \gamma_5\}$

$\Gamma_q \in \{1, \gamma_5, \gamma_\mu, \gamma_\mu \gamma_5\}$

If $\Gamma_\chi, \Gamma_q \in \{1, \gamma_5\}: \; G_\chi = m_q/(2M_*^3)$ (chirality violating!), else $\Gamma_\chi = 1/(2M_*^2)$ Rajamaran, Shepherd, Tait, Wijango, arXiv:1108.1196.

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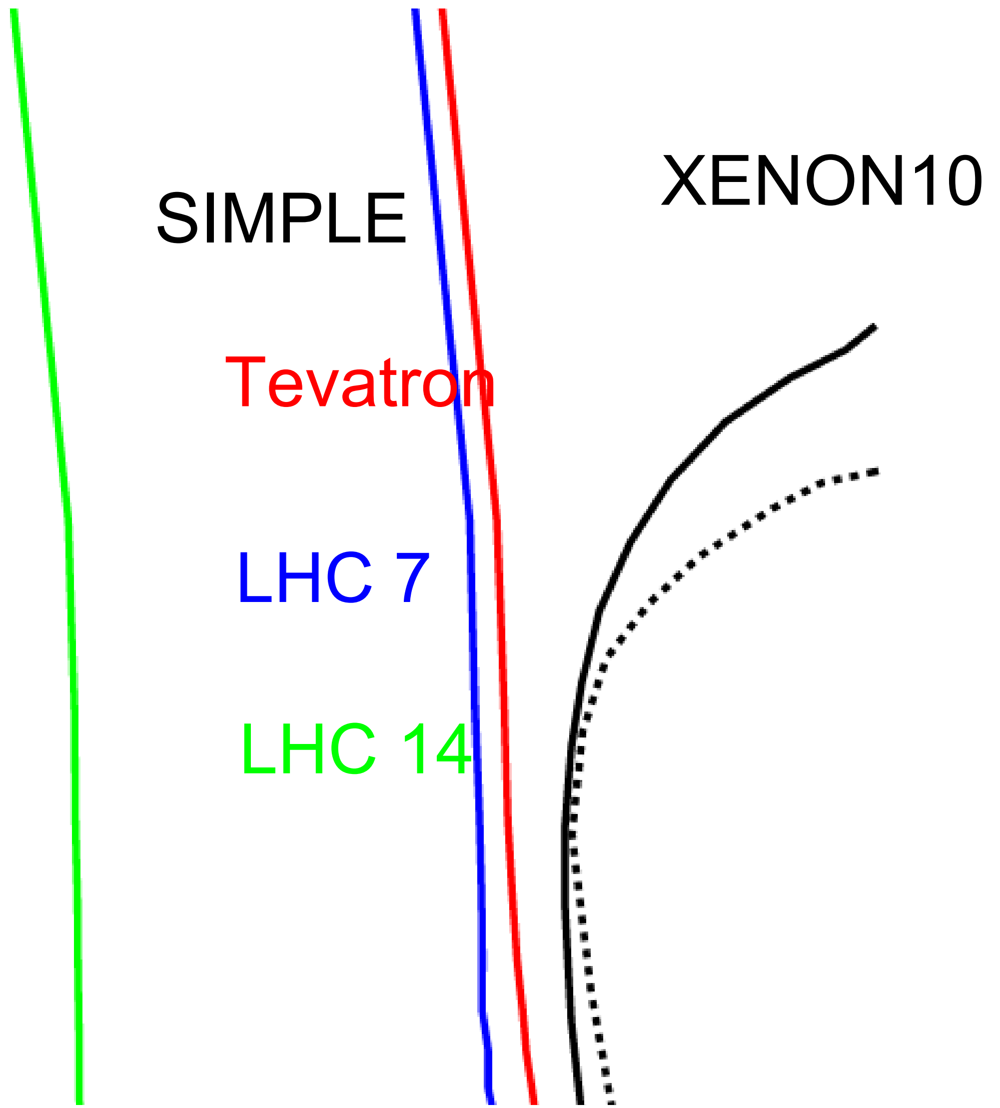
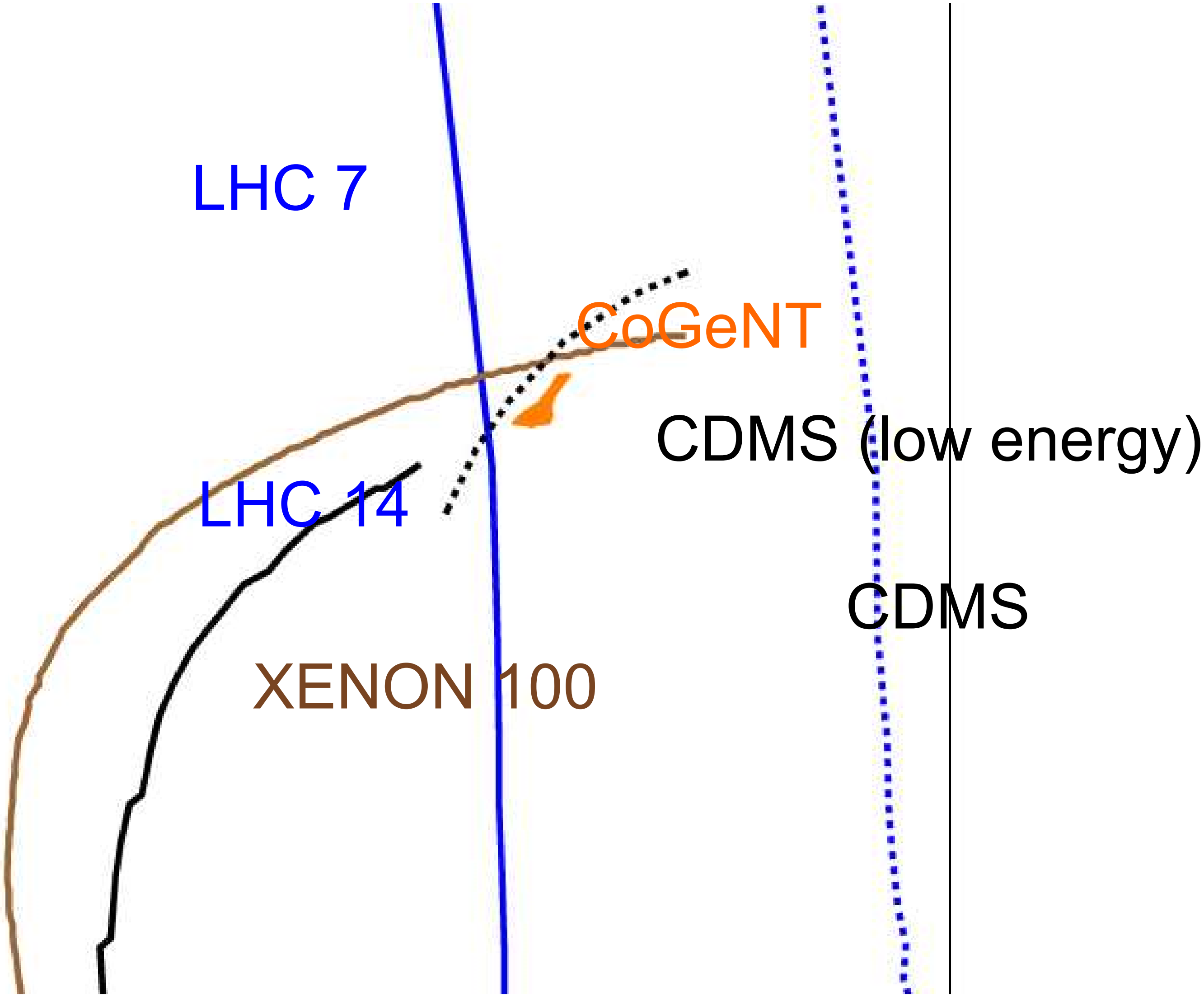
Compute monojet signal from $q\bar q \rightarrow \chi\chi g$, compare with monojet limits (current bound) and background (ultimate reach)!

$\Gamma_\chi = \gamma_\mu \gamma_5$ (corr. to spin-dep. interact.)



$\Gamma_\chi = 1$ (corr. to spin-indep. interact.)



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Altogether: very limited usefulness for most actual WIMP models.

2 DM and Light (Gauge) Bosons

(At least) 3 kinds of WIMP models require light ($m \leq$ few GeV) (gauge) bosons U:

- MeV DM: Suggested as explanation of 511 keV line ($\Longrightarrow$ slow e^+) excess from central region of our galaxy (Boehm et al., astro-ph/0309686). Should have $m_\chi \leq 10$ MeV (γ constraints)
  $\Longrightarrow m_\chi \leq m_U \leq 200$ MeV to mediate $\chi\chi \to e^+e^-$; fixes $g_{U\chi\chi} g_{Ue^+e^-}/m_U^2$! (Unless $2m_\chi \simeq m_U$.)

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- PAMELA/FermiLAT inspired TeV DM: Needs light boson for Sommerfeld enhancement (e.g. Arkani-Hamed et al., arXiv:0810.0713(4)) ($\chi\chi \rightarrow UU \rightarrow 4l$ is also somewhat less constrained by γ spectrum than $\chi\chi \rightarrow 2l$.)

- DAMA/CoGeNT inspired few GeV DM: Needs light mediator to achieve sufficiently large $\sigma_{\chi p}$. (2 different mediators for isospin violation to evade bounds: Cline, Frey, arXiv:1108.1391)

Light Gauge Bosons (cont'd)

In all cases: U couplings to (most) SM particles must be $\ll 1$ to evade bounds! ($g_\mu - 2$, meson decays, ν cross sections, APV, $\ldots$).

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$U\chi\chi$ coupling may well be large.

Signatures of light gauge bosons

If $m_U > 2m_\chi$: $U \to \chi\chi$ dominant! Is invisible $\Longrightarrow$ need extra tag, e.g. $e^+e^- \to \gamma U \to \gamma +$ nothing.

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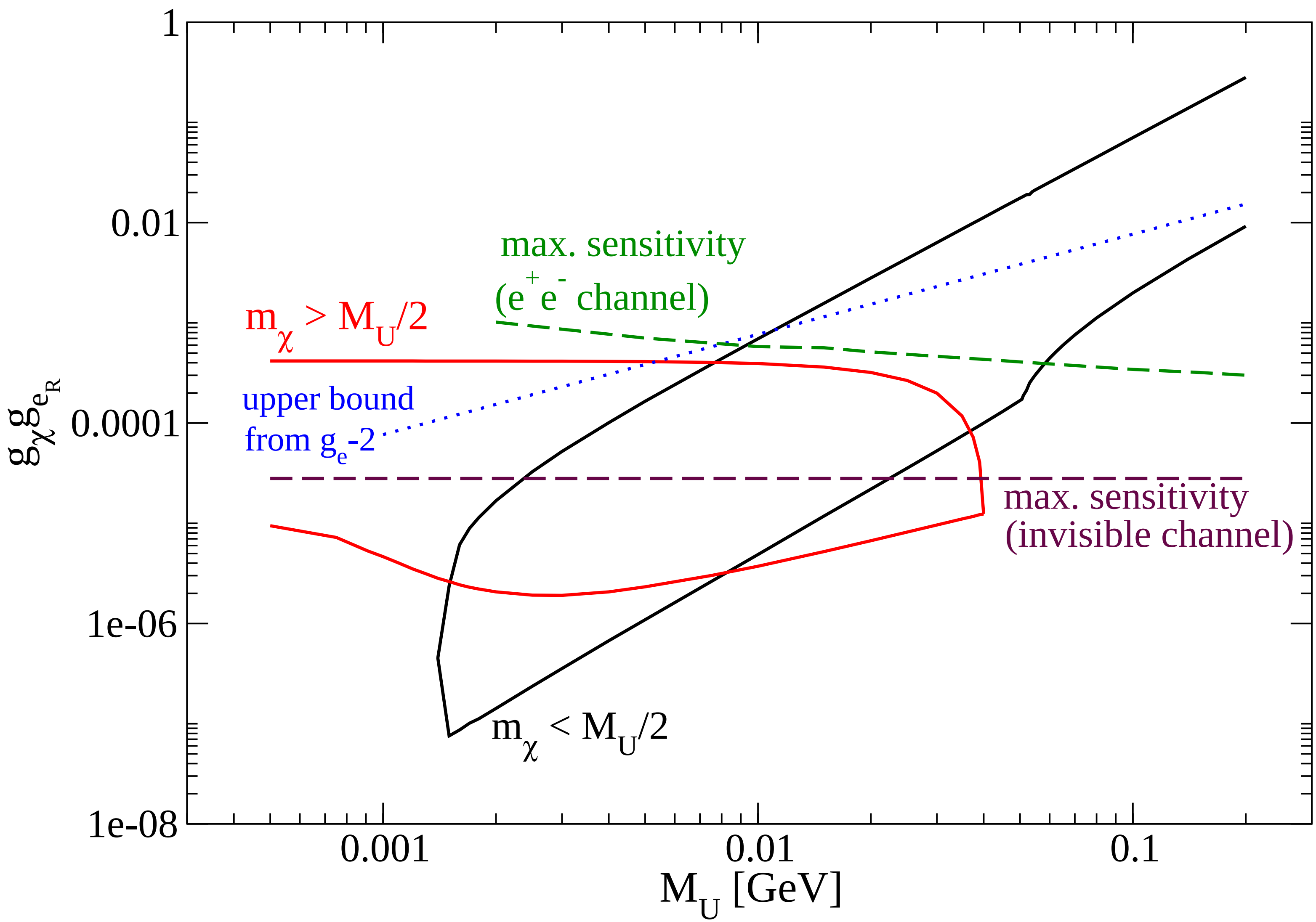
- Instrumental backgrounds (not from e^+e^- annihilation) seem large

Sensitivity at $B-$factories (100 fb^{-1})



Red, black: Regions allowed by Ω_χ, $\sigma(\chi\chi \to e^+e^-)$.

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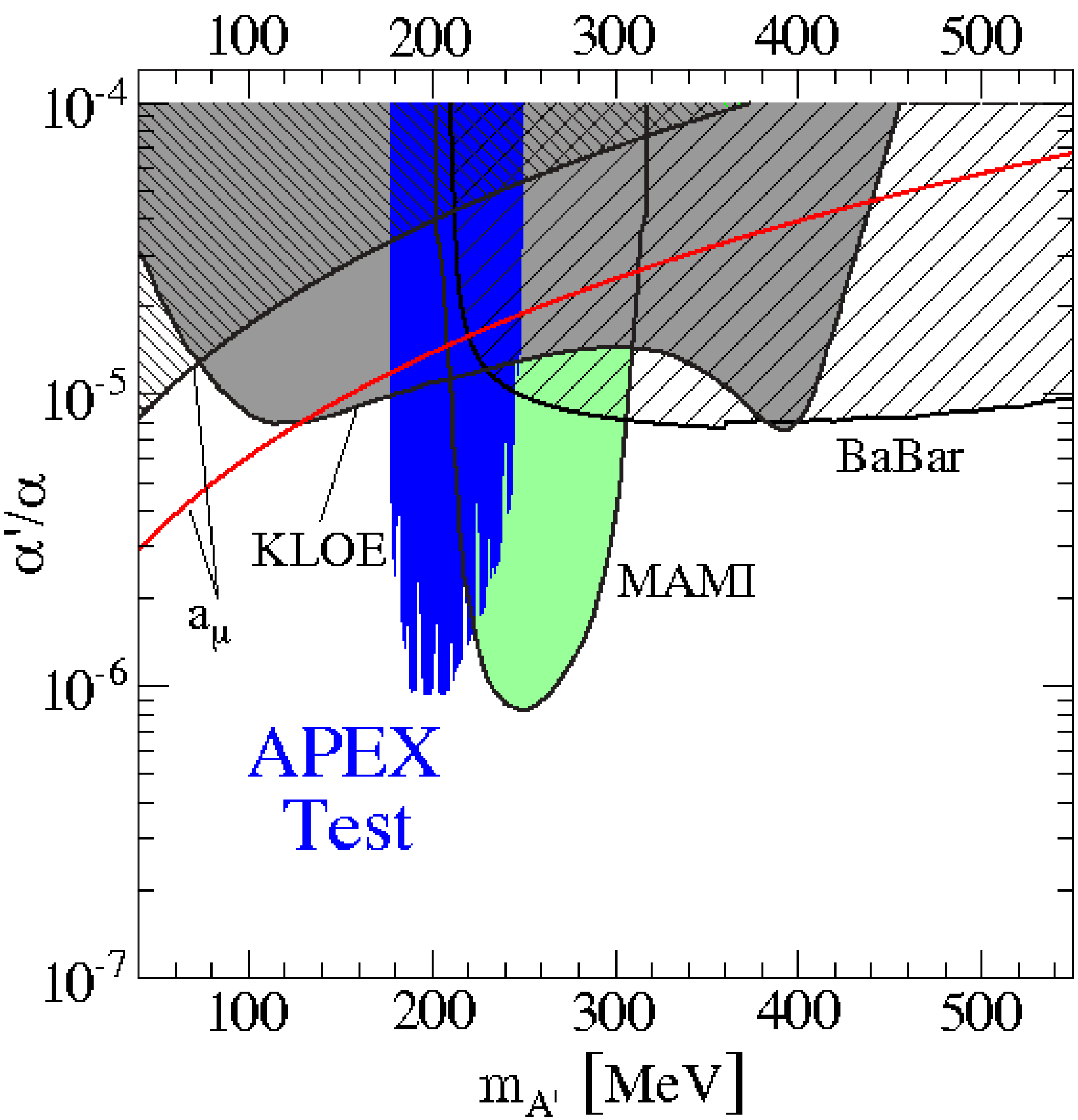
Also, KLOE-2 performed search, mostly for $\phi \to U\eta$: no signal. arXiv:1107.2531

A1 and APEX results



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- HLS theorem, relation to superstrings: don't single out weak scale.

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- In simplest, $R-$parity invariant scenario: lightest superparticle LSP is stable: satisfies one condition for DM candidate!

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- but DM–allowed regions of parameter space do exist even in constrained models!

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- Note: DM–allowed region of $(m_0, m_{1/2})$ plane of cMSSM depends on $A_0, \tan\beta$!

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- $\tilde{\tau}_1$ co–annihilation requires $m_{\tilde{q}} \leq m_{\tilde{g}}$: good for LHC searches; still plenty of allowed region left.

Impact of Indirect DM Searches

- No halo signal in co–annihilation region; ν from Sun small

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- Most interesting to me: Predict $\Omega_\chi h^2$, compare with observation: Constrain very early universe!

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Two approaches: Case studies, broad scans of parameter space

Case study: $\tilde{\tau}_1$ co–annihilation region in cMSSM

Arnowitt et al., arXiv:0802.2968

- Needs $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} \leq 15$ GeV
  $\Longrightarrow \tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau,\ \tilde{\chi}_1^{\pm} \to \tilde{\tau}_1^{\pm} \nu_\tau$ have nearly unit branching ratio
  $\Longrightarrow$ no di–lepton edges!

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- Study three classes of final states:
  (i) $2\tau + 2j + \not{E}_T$
  (ii)$4 \text{ non} - b\ j + \not{E}_T$
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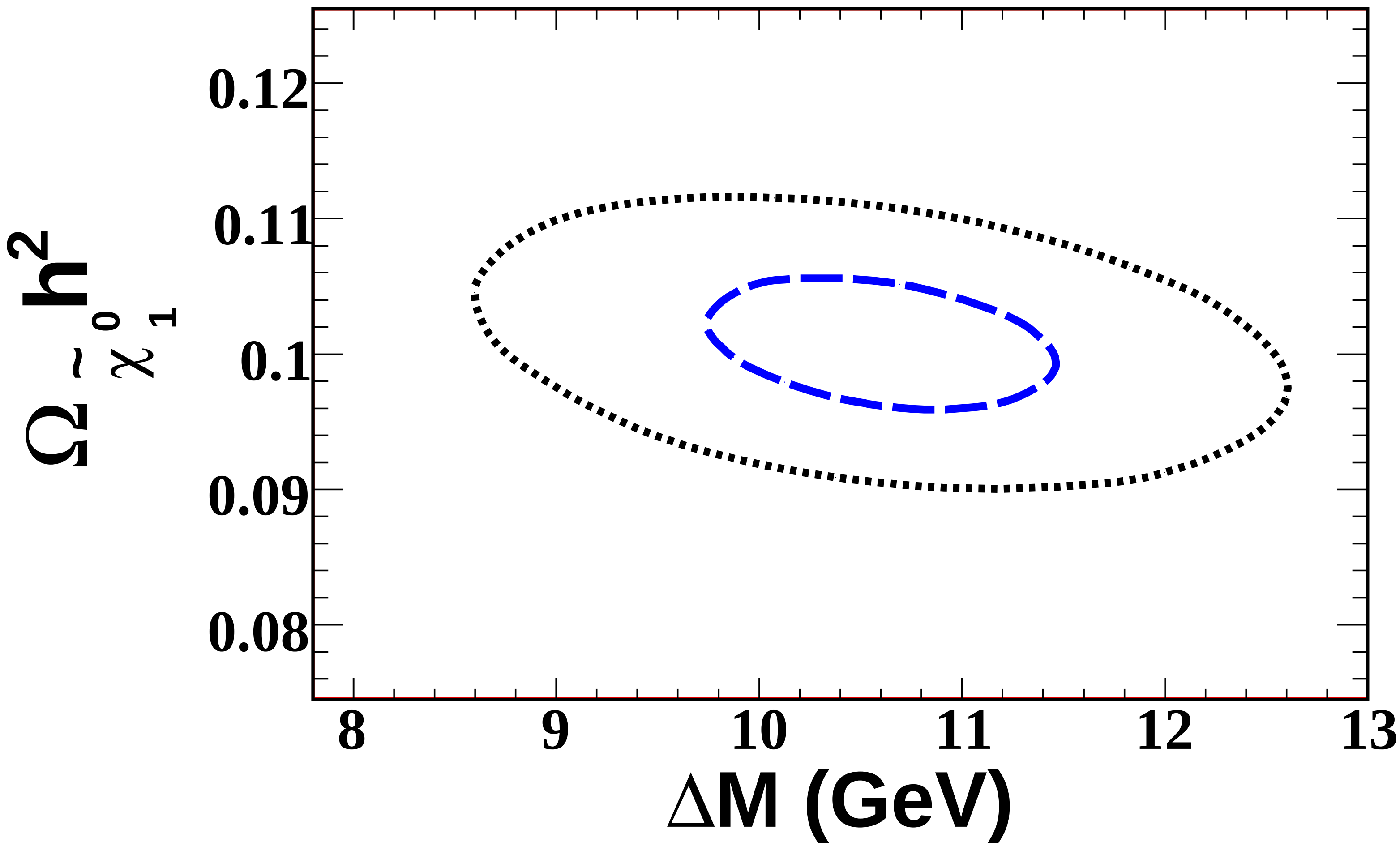
  (iii) leading $b + 3j + \not{E}_T$
- Fit many kinematical distributions simultaneously, including slope of softer p_T^τ spectrum in sample (i) $\Longrightarrow$ predict $\Omega_{\tilde{\chi}_1^0} h^2$ to 10%!

Result of fit



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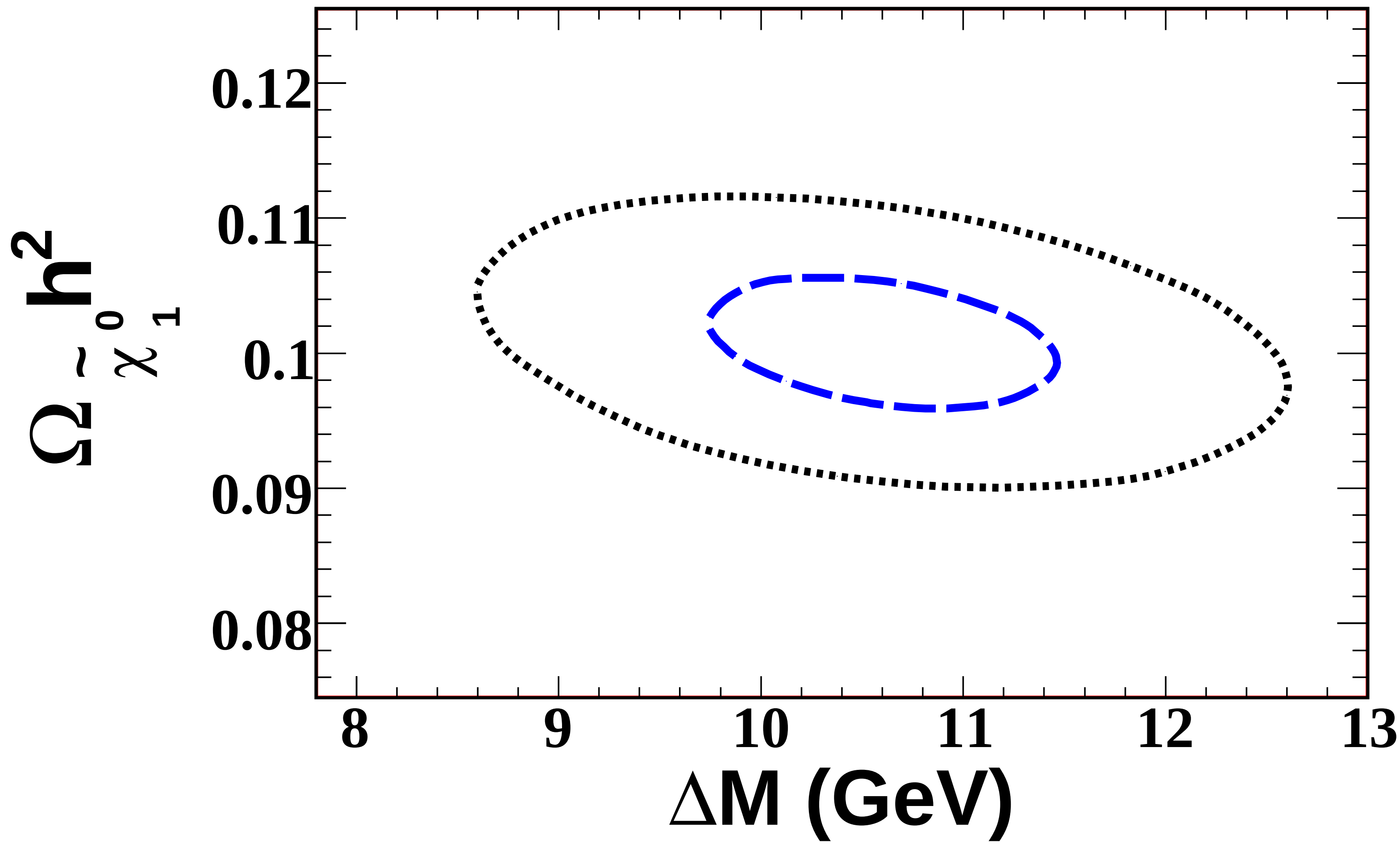

Unfortunately, chosen benchmark point ($m_{\tilde{g}} = 830$ GeV, $m_{\tilde{q}} \simeq 750$ GeV) is most likely excluded!

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$$(\Delta S_{AB})^2 = \frac{1}{n_{\rm sig}} \sum_{i=1}^{n_{\rm sig}} \left(\frac{s_i^A - s_i^B}{\sigma_i^{AB}} \right)^2$$

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MC: $(\Delta S_{AB})^2 > 0.285 \Longrightarrow$ models differ at > 95% c.l.

Results and Remarks

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- Statistics looks weird! Comparing two simulations of same “model”, get 611 (out of 2600) cases where some 2ℓ observable has $> 5\sigma$ discrepancy: *way* too many!

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Bornhauser and MD, in progress

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- Define proper χ^2, incl. corr. between $\langle n_j \rangle$, $\langle n_j^2 \rangle$, only including significant observables: test with MC.

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- Introducing SM background, but no syst. error: 10 pairs have $p > 0.05$

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- Higgs searches can also be used to distinguish between WIMP models and to help determine parameters. E.g. m_h in MSSM constrains stop sector.

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- Higgs sector also very important for WIMP physics!